Astronomy & Astrophysics manuscript no. Fh042
(DOI: will be inserted by hand later)

February 2, 2008

Simultaneous multi-wavelength observations of GRS 1915+105★

Y. Fuchs[1], J. Rodriguez[1,2], I.F. Mirabel[1,3], S. Chaty[1,4], M. Ribó[1], V. Dhawan[5], P. Goldoni[1], P. Sizun[1], G.G. Pooley[6], A.A. Zdziarski[7], D.C. Hannikainen[8], P. Kretschmar[9,2], B. Cordier[1], N. Lund[10]

1 Service d'Astrophysique (CNRS FRE 2591), CEA Saclay, 91191 Gif-sur-Yvette Cedex, France
2 Integral Science Data Center, Chemin d'Ecogia, 16, CH-1290 Versoix, Switzerland
3 Instituto de Astonomía y Física del Espacio / CONICET, cc67, suc 28. 1428 Buenos Aires, Argentina
4 Université Paris 7, Fédération APC, 2 place Jussieu, 75005 Paris, France
5 National Radio Astronomy Observatory, Socorro, NM 87801, USA
6 Mullard Radio Astronomy Observatory, Cavendish Laboratory, Madingley Road, Cambridge CB3 0HE, UK
7 N. Copernicus Astronomical Center, Bartycka 18, 00-716 Warsaw, Poland
8 Observatory, PO Box 14, FIN-00014 University of Helsinki, Finland
9 Max-Planck-Institut fuer Extraterrestrische Physik, Giessenbachstrasse, 85748 Garching, Germany
10 Danish Space Research Institute, Juliane Maries Vej 30, DK-2100 Copenhagen Oe, Denmark

Received ; accepted

Abstract. We present the result of multi-wavelength observations of the microquasar GRS 1915+105 in a plateau state with a luminosity of $\sim 7.5 \times 10^{38}$ erg s^{-1} ($\sim$40% $L_{\rm Edd}$), conducted simultaneously with the INTEGRAL and RXTE satellites, the ESO★★/NTT, the Ryle Telescope, the NRAO★★★ VLA and VLBA, in 2003 April 2–3. For the first time were observed concurrently in GRS 1915+105 all of the following properties: a strong steady optically thick radio emission corresponding to a powerful compact jet resolved with the VLBA, bright near-IR emission, a strong QPO at 2.5 Hz in the X-rays and a power law dominated spectrum without any cutoff in the 3-400 keV range.

Key words. Stars: individual: GRS 1915+105 – X-rays: binaries – Gamma rays: observations – ISM: jets and outflows

1. Introduction

Microquasars are galactic X-ray binaries exhibiting relativistic jets (Mirabel & Rodríguez 1999). The microquasar GRS 1915+105 has been extensively observed since this source is known to be extremely variable at all wavelengths (see Fuchs et al. 2003 for a review). It hosts the most massive known stellar mass black hole of our Galaxy with $M = 14 \pm 4 M_{\odot}$ (Greiner et al. 2001a). It was the first galactic source to show superluminal ejections (Mirabel & Rodríguez 1994) in the radio domain, which has enabled to give an upper limit of 11.2±0.8 kpc to the distance of the source (Fender et al. 1999). In addition to these arcsecond scale ejections, GRS 1915+105 sometimes produces a compact jet which has been resolved at milli-arcsecond scales in radio (Dhawan et al. 2000), corresponding to a length of a few tens of AU. The presence of such a compact and quasi-steady radio jet is now commonly inferred in the low/hard X-ray state of several microquasars but it is rarely resolved (see Fender 2003 and references therein).

We present here the first multi-wavelength campaign on GRS 1915+105 involving the recently launched INTErnational Gamma-Ray Astrophysics Laboratory (INTEGRAL, 3 keV–10 MeV). This campaign was conducted by the MINE[1] (Multi-λ INTEGRAL NEtwork) international collaboration aimed at performing multi-wavelength observations of galactic X-ray binaries simultaneously with the INTEGRAL satellite. In Sect. 2 we present an overview of our campaign, our results are shown in Sect. 3 and discussed in Sect. 4.

2. Overview of the multi-wavelength campaign

We conducted a multi-wavelength observation campaign of GRS 1915+105 in March-April 2003. In this letter we focus only on April 2–3, when we obtained data covering the widest range of frequencies, with the largest number of involved instruments observing simultaneously with INTEGRAL (Fig. 1).

Send offprint requests to: Y. Fuchs, e-mail: yfuchs@cea.fr

★ Based on observations with INTEGRAL, an ESA project with instruments and science data centre funded by ESA member states (especially the PI countries: Denmark, France, Germany, Italy, Switzerland, Spain), Czech Republic and Poland, and with the participation of Russia and the USA.

★★ Based on observations collected at the European Southern Observatory, Chile (ESO N°071.D-0073).

★★★ The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

1 See http://elbereth.obspm.fr/~fuchs/mine.html.

These observations are ToO (Targets of Opportunity) triggered by the MINE collaboration under the INTEGRAL Guaranteed Time Programme (PI Mirabel) and related programmes on the other instruments[2]. The detailed analysis of the whole campaign, i.e. March 24–25, April 2–3 and April 17–18 2003 (Fig. 2) including further instruments, will be presented in forthcoming papers. We thus present here an overview of the results of a (nearly) simultaneous campaign involving the Very Large Array (VLA), the Very Long Baseline Array (VLBA) and the Ryle Telescope (RT) in radio, the ESO New Technology Telescope (NTT) in IR, the Rossi X-ray Timing Explorer (RXTE) and INTEGRAL in X and γ-rays.

2.1. INTEGRAL

The data from the Integral Soft Gamma Ray Imager (ISGRI, 15 keV–1 MeV, Lebrun et al. 2003), were reduced with the Off-line Scientific Analysis software (OSA) v2.0 following Goldwurm et al. (2003). The total elapsed time resulted in ~101 ks divided in 46 independent science windows (scw). For each of them we produced images in 2 energy bands, 20–40 keV and 40–80 keV, where GRS 1915+105 was clearly detected and from which we could obtain its position and flux. The spectral extraction was performed independently for every scw in 128 channels linearly rebined in the 20–1000 keV range. Given the low level of variability (less than 20%, see Fig. 1), the resultant spectra were combined with *mathpha*, and fitted between 20 and 400 keV with *xspec* v11.2 (also used for the SPI and RXTE spectral fits). Note that we also produced spectra with the officially available 13–1000 keV matrix. The results show no significant differences when fitting the spectra in the 20–400 keV range.

For the Spectrometer on board Integral (SPI, 20 keV–8 MeV, Vedrenne et al. 2003), after correction of the misalignment, we extracted simultaneously the spectra of 6 sources seen by ISGRI in the 20–40 keV band. We extracted the spectra of both the sources and background with the standard *spiros* programme (Skinner & Connell 2003), using the latest derived response matrix (Sturner et al. 2003). The observation being made in dithering mode, we were able to resolve the background in each energy bin and each detector independently.

Using OSA v2.0, JEM-X (Joint-European Monitor for X-rays, 3–35 keV, Lund et al. 2003) spectra were extracted (Westergaard et al. 2003) for the 42 scw where the source was within 5°of the pointing direction and then combined for a total exposure of ~88 ks. The latest responses were used but the effective area corrected by a factor of 2 for the known losses due to dead anodes and the exclusion of the outermost areas of the detector.

[2] Except for the RXTE observations which are part of a larger simultaneous INTEGRAL/RXTE campaign on GRS 1915+105 (PIs Hannikainen, Rodriguez), for which the RXTE planning team kindly agreed to schedule an observation during the INTEGRAL ToO presented here.

2.2. RXTE

The RXTE observations were reduced following the standard procedure for bright sources, using the LHEASOFT package v5.2. See e.g. Rodriguez et al. (2003), for the details of the Proportional Counter Array (PCA, 2–60 keV) and High Energy X-ray Timing Experiment (HEXTE, 20–200 keV) data reduction followed for the spectral extraction and analysis (note that we only extracted spectra from the proportional counter unit 0 and 2 for the PCA). We also extracted light curves with ~4 ms resolution from the PCA (see Fig. 1), and produced power spectra with *powspec* 1.0.

2.3. Infrared

The near infrared observations were performed with the 3.58 m ESO/NTT through a ToO programme (PI Chaty) dedicated to observations of high energy transient sources. The telescope was equipped with the IR spectrograph and imaging camera SOFI. We took images in the broad band filters J (1.247 ± 0.290 μm), H (1.653 ± 0.297 μm) and K_s (2.162 ± 0.275 μm) with a 4.9′×4.9′ field of view (0.292″/pixel). Nine images of 60 s integration time were acquired in each filter and co-added. We also observed in the K_s-band with high temporal resolution (see Fig. 1), taking 450 exposures of 2 s each, by averaging 9×2 s frames, and randomly offsetting in distance and direction between each frame, during nearly 2.3 hours. The images were reduced using the IRAF suite. Each image was corrected by a normalized dome-flat field, and sky-subtracted by a sky image (median filter combination of 9 consecutive images). The data were then analysed using *apphot*. Absolute photometry was performed using 2 standard stars: HST P499-E and HST S808-C (Persson et al. 1998). The conditions were photometric for most of the observations, the seeing being typically 0.8″.

2.4. Radio

We observed the source during two hours on April 2, 2003 with the VLBA at 2.0 and 3.6 cm (ToO programme, PI Ribó). The observing strategy was the same as the one described in Dhawan et al. (2000). A detailed analysis of all the VLBA data acquired during this campaign will be presented in Ribó et al. (2003). The simultaneous radio light curve obtained with the VLA at 3.6 cm (8.4 GHz) during the first hour of the VLBA observations reveals a nearly constant flux density of 160±1 mJy (1σ error, see Fig. 1), providing good confidence in the obtained VLBA images.

The Ryle Telescope observations at 15 GHz are part of a continuing monitoring program (see Pooley & Fender 1997 for more details). The data are shown in Figs. 1 & 2 with 5 min averaging; the typical uncertainty is 2 mJy + 3% in flux scaling.

3. Results

Figure 2 shows the general radio and X-ray behaviour of GRS 1915+105 during our observing campaign. Despite X-ray and giant radio flaring episodes that occurred in March–April 2003, our multi-wavelength observations took place dur-

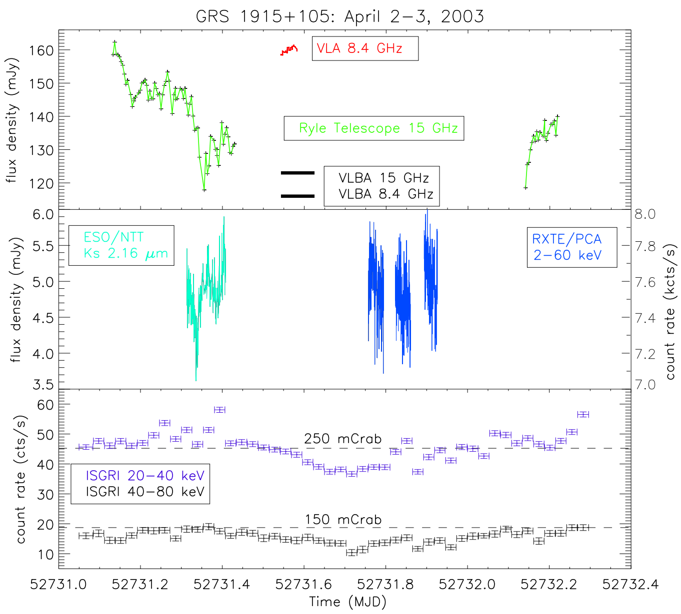

Fig. 1. Light curves of the multi-wavelength observations on April 2–3, 2003 involving INTEGRAL/ISGRI & SPI (not plotted), RXTE/PCA & HEXTE (not plotted), ESO/NTT, RT, VLA and VLBA (total flux densities spanning the observing time).

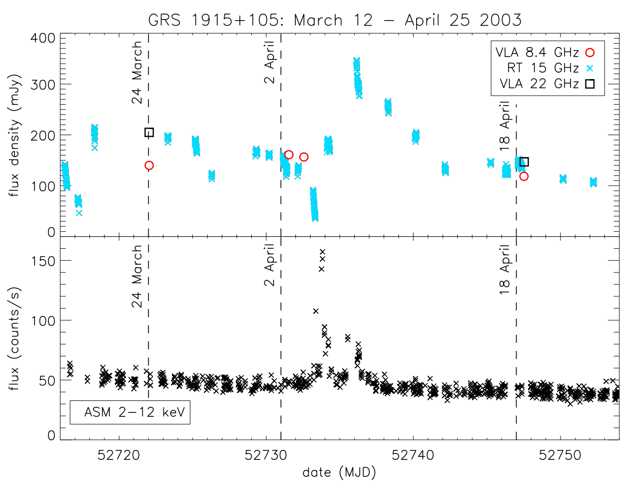

Fig. 2. Radio and X-ray flux monitoring of GRS 1915+105 in March-April 2003. Radio: VLA at 8.4 & 22 GHz, RT at 15 GHz. X-ray: quick-look results provided by the ASM/RXTE team. The dashed lines indicate the dates of our INTEGRAL and simultaneous multi-wavelength observations.

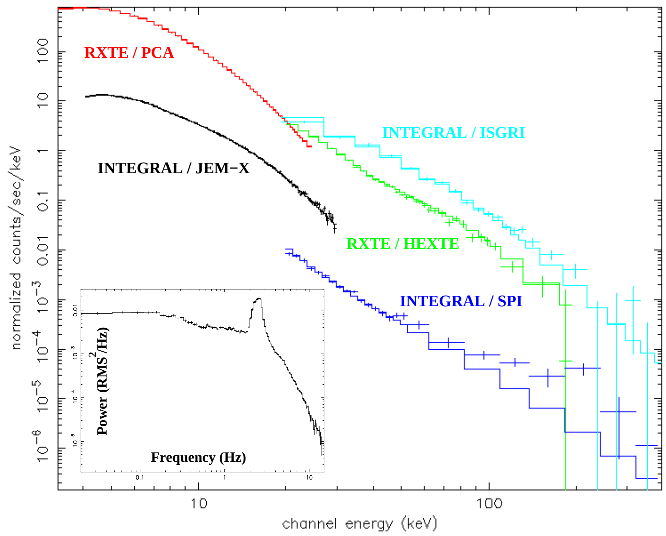

Fig. 3. X-ray and γ-ray spectra of GRS 1915+105 measured with RXTE (PCA and HEXTE) and INTEGRAL (JEM-X, ISGRI and SPI) on April 2, 2003. Different sensitivities of the instruments lead to different levels of the spectra when plotted in count rates (which enables a better display). The structures at E>50 keV in the SPI spectrum are instrumental background lines not adequately corrected. Continuous lines are the best fits with the models described in the text, showing consistent photon indexes among the different instruments. The PCA power density spectrum (inset) shows a clear QPO at 2.5 Hz.

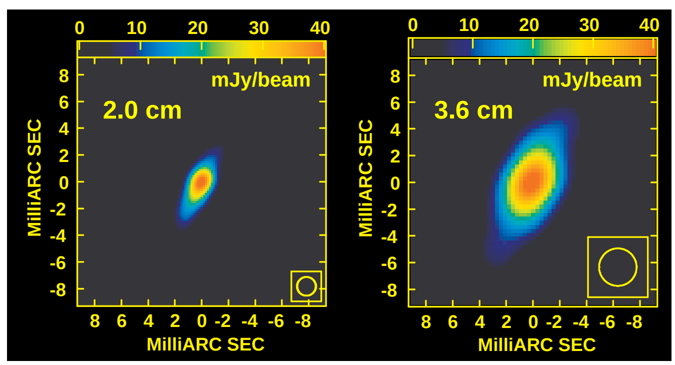

Fig. 4. VLBA images at 2.0 & 3.6 cm on April 2, 2003 showing the compact jet. Total integrated flux densities are 123 & 116 mJy, respectively, in agreement with a slightly inverted spectrum. The convolving beams are 1.4 & 2.8 mas, respectively. 1 mas corresponds to 12 AU at 12 kpc distance. The rms noise in both maps is 0.15 mJy beam^{-1}.

ing quasi-quiet periods, with a slowly decaying ASM flux ~ 50 cts/s and an unusually high radio level (>100 mJy).

The accumulated spectra obtained with INTEGRAL (ISGRI and SPI) and with RXTE (PCA and HEXTE) on April 2–3 are shown in Fig. 3. The ISGRI and SPI spectra are well jointly fitted in the 20–400 keV range by a power law with a photon index of $\Gamma = 3.16 \pm 0.04$ which is flatter than the $\Gamma = 3.58 \pm 0.02$ index of the HEXTE spectrum in the 20–200 keV range. This difference may be due to either instrument, since the background noise of HEXTE is uncertain when pointing in the galactic plane, and the calibration (e.g. background correction) of ISGRI and SPI are still in progress. Moreover, the HEXTE spectrum is built only on ~6 ks of observation whereas the INTEGRAL spectra are averaged over 101 ks.

The PCA + HEXTE spectrum (3–200 keV, cf Fig. 3) was fitted by the sum of a multicolor blackbody model (diskbb), a power law and an iron line at ~6 keV assuming a interstellar absorption with $N_{\rm H} = 5 \times 10^{22}$ cm^{-2}. The fitted power law, with $\Gamma = 2.94 \pm 0.01$, accounts for 77% of the total unabsorbed 3–20 keV flux, and is flatter than at higher energies where the soft component has no longer influence. The resulting inner disk temperature is very high ($kT > 3$ keV) as al-

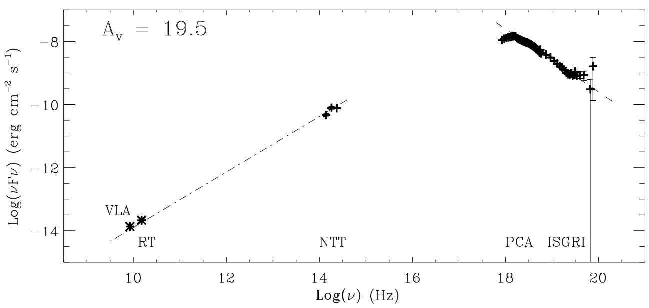

Fig. 5. Spectral energy distribution of GRS 1915+105 on April 2. The near-IR flux densities were dereddened with $A_V = 19.5$ and using eq. 1 of Cardelli et al. (1989). The dot-dashed line illustrates the optically thick synchrotron emission from the jet as a power law with $F_\nu \propto \nu^{-0.12}$. The dashed line illustrates a power law with a photon index Γ=3. Error bars not shown are smaller than the symbol size.

ready noticed by Muno et al. (1999, 2001) who obtained similar results while fitting the plateau state of GRS 1915+105 (cf discussion), which may indicate either that the diskbb model is not valid here, or that other emission processes, such as Comptonization in thermal plasma (Zdziarski et al. 2001), are responsible for the low energy X-ray component. An analysis of the averaged spectrum obtained with JEM-X gives spectral fits (4–30 keV) consistent with the PCA. The estimated luminosity is $\sim 7.5 \times 10^{38}$ erg s^{-1} corresponding to ~40% of the Eddington luminosity for a $14 M_\odot$ black hole. As shown in Fig. 3, a very clear Quasi-Periodic Oscillation (QPO) at 2.5 Hz with a 14% rms level was observed in the RXTE/PCA signal.

The VLBA high resolution images (Fig. 4) show the presence of a compact radio jet with a ~7–14 mas length (85–170 AU at 12 kpc). This jet is very similar to the one observed by Dhawan et al. (2000) and is responsible for the high radio levels measured with the RT and the VLA (Fig. 2) by its optically thick synchrotron emission.

The source was fairly bright in near-IR (compare e.g. to Chaty et al. 1996) with apparent magnitudes $J = 17.19 \pm 0.06$, $H = 14.46 \pm 0.12$ and $K_s = 12.95 \pm 0.14$. This corresponds to an excess of 75% to 85% in the K_s-band flux compared to the K=14.5-15 mag. of the K-M giant donor star of the X-ray binary (Greiner et al. 2001b). The spectral energy distribution of Fig. 5 is compatible with a strong contribution to the near-IR bands from the synchrotron emission of the jet extending from the radio up to the near-IR. However, the J, H, and K_s dereddened flux densities are not compatible with such a single power law emission, since a significant change in the slope appears at the H-band by dereddening with a visible absorption $A_V = 19.5$ (Chapuis & Corbel 2003). We point out here that while the value of the visible absorption is still a matter in the debate (see e.g. Fuchs et al. 2003 and Chaty et al. 1996), this H band excess might be due to the sum of the different components adding to the jet emission in the near-IR, such as the donor-star, the external part of the accretion disc or a free-free emission.

The detailed light curves of our observations (Fig. 1) show nearly quiet flux densities when compared to flares or oscillations, with variations ≲20% at all wavelengths. The most interesting phenomenon is a moderate ~25% decrease (from 4.9 to 3.6 mJy) in the K_s flux density lasting 20 min which precedes by 31 min a ~20% decrease in the RT signal (from 145 to 118 mJy) lasting 48 min. This may be due to instabilities in the jet inducing an immediate synchrotron response in the IR and the delay being due to the time for the material along the jet to become optically thin to the radio emission (Mirabel et al. 1998).

4. Discussion

Bright radio emission ($F_\nu \gtrsim 100$ mJy at 15 GHz) accompanied by steady X-ray emission (ASM ~50 cts/s) similar to what happened around April 2, 2003 were observed on several past occasions in GRS 1915+105 (see e.g. Fig. 1 of Muno et al. 2001). This state is known as the plateau state (Fender et al. 1999; Klein-Wolt et al. 2002 and references therein) but is also called the radio loud low/hard X-ray state (Muno et al. 2001) and type II state (Trudolyubov 2001). It also corresponds to the χ_1 and χ_3 X-ray classes of Belloni et al. (2000) who used PCA color-color diagram, and indeed our April 2 observation appears as the χ_1 class when plotted in such a diagram. Dhawan et al. (2000) observed GRS 1915+105 with the VLBA during the 1998 plateau state, and they found a compact radio jet very similar to the one shown in Fig. 4.

The strong QPO at 2.5 Hz observed on April 2 is consistent with the low/hard state of GRS 1915+105. The presence of the 0.5–10 Hz QPO seems correlated to a hard tail in the energy spectra of the source (Markwardt et al. 1999; Muno et al. 1999), although the energy dependence of the QPO amplitude might show a cut-off at high energy (Rodriguez et al. 2002), indicating that the QPO is probably not related to a global oscillation of that hard component.

The high energy emission of GRS 1915+105 on April 2 is also consistent with the low/hard state of the source, with a power law dominated spectrum (77% at 3–20 keV), although always softer (Γ~3) than for the other BH binaries (McClintock & Remillard 2003). The INTEGRAL observations show that this power law spectrum extends up to 400 keV without any cutoff during this plateau state, consistent with the observations with OSSE (Zdziarski et al. 2001).

Here for the first time, we observed simultaneously all the properties of the plateau state of GRS 1915+105 that were previously observed individually. We thus confirm the presence of a powerful compact radio jet, responsible for the strong steady radio emission and probably for a significant part of the bright near-IR emission, as well as a QPO (2.5 Hz) in the X-rays and a power law dominated X-ray spectrum with a Γ~3 photon index up to at least 400 keV. Detailed fits of the RXTE and INTEGRAL spectra of GRS 1915+105 in this plateau state, to determine for example whether this power law is due to an inverse Compton scattering of soft disc photons on the base of the compact jet (see e.g. Fender et al. 1999; Rau & Greiner 2003) or not, will be studied in forthcoming papers. In our multi-wavelength March-April campaign, the source was observed essentially in the plateau state. In order to better understand the unusual behaviour of GRS 1915+105, we need to carry out

similar simultaneous broad-band campaigns during the other states, in particular during the sudden changes in the X-ray state that correspond to powerful relativistic ejection events.

Detailed analysis and interpretation of all of our observations and their scientific implications will be presented, separately, in future articles.

Acknowledgements. Y.F. and J.R. acknowledge financial support from the CNES. M.R. acknowledges support from a Marie Curie individual fellowship under contract No. HPMF-CT-2002-02053. D.C.H. acknowledges the Academy of Finland for financial support. A.A.Z. has been supported by KBN grants 5P03D00821, 2P03C00619p1,2 and PBZ-054/P03/2001. S.C. is grateful to skills and availability of the ESO staff for performing ToO programmes, and particularly to the support astronomer Emanuela Pompei.

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